

Exploring Techniques for Improving Retrievals of Bio-optical Properties of Coastal Waters

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LONG-TERM GOALS

Development of algorithms for improved retrievals of inherent water optical properties (IOP) from satellite imagery of coastal waters with current and future sensors utilizing: 1) NIR and UV channels, 2) water polarization characteristics and 3) advanced atmospheric correction schemes.

OBJECTIVES

Analysis of methodologies for the enhancement of algorithms for IOP retrieval from reflectance spectra based on additional measurements in NIR and UV through: a) the use of reflectance characteristics obtained from NIR measurements as additional constraints in basic inversion models, b) expansion of modeled and measured reflectance spectra and bio-optical models of coastal waters into the UV zone for the improved separation of CDOM and phytoplankton components.

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Utilization of underwater and above water polarization components of reflectance spectra for the improvement of particle type discrimination and algorithm development through: a) the simulation of polarization components of reflectance for coastal water environments using polarized radiative transfer and b) measurements of polarization characteristics in field conditions to validate radiative transfer modeling and assess possibilities for the separation of organic and inorganic particulate components.

Improvement in retrievals of water leaving radiances for productive coastal waters obtained by adding the 412nm channel to the SWIR coastal algorithm Improve on existing atmospheric correction algorithms in highly productive coastal waters by combining both long wave atmospheric channels with shortwave water leaving constraints at 412nm along with a more representative aerosol database.

A new objective was added for this year: **Development of an offshore platform in coastal waters** which can serve as a new AERONET Ocean Color site in US waters as well as a site for comprehensive calibration/validation of the current and future Ocean Color satellite sensors including hyperspectral sensors and instruments with polarization sensitivity. A significant part of this task is currently done through leveraged funding.

APPROACH

Analysis of methodologies for the enhancement of algorithms for IOP retrieval from reflectance spectra based on additional measurements in NIR and UV

The NIR peak in reflectance spectra from coastal waters contains important information about chlorophyll concentration Chl and other parameters used in retrieval algorithms. Available NIR algorithms for Chl retrieval are compared and their robustness in various water conditions evaluated. Optical properties of toxic *Karenia Brevis* (*K. brevis*) algae were analyzed with the goal of developing algorithms satellite detection and distinction of *K. brevis* algal blooms.

Adding UV channels to VIS and NIR channels can improve separation of CDOM and Chl absorption components. To analyze their impact, neural network inversion algorithms were used, together with a Hydrolight simulated database of reflectances for a wide variety of coastal water conditions, expanded to cover the 300-400 nm range and combined with field data to test improvements in retrievals resulting from the inclusion of the UV channels.

Utilization of underwater and above water polarization components of reflectance spectra for the improvement of particle type discrimination and algorithm development

The thrust of this part of the work is to obtain above and underwater angularly resolved hyperspectral field measurements of the degree of polarization (DOP) in wide variety of coastal environments using our newly developed Stokes vector spectroradiometer, and compare results with simulated data. Differences in polarization signatures of inorganic and organic particles can be further used in the improved interpretation of remote sensing signals and in comparisons with the polarization signatures of important naval targets as supplied by NRL with the goal of improvement of visibility and detection.

Improvement in retrievals of water leaving radiances for productive coastal waters obtained by adding the 412nm channel to the SWIR coastal algorithm To counter problems with operational NIR algorithm [1-3], an algorithm using short wave infrared (SWIR) bands (i.e. MODIS 1240 and

2130nm) was proposed for operational retrieval of coastal water color and tested within SeaDAS [4]. However, at these long wavelengths, the atmospheric reflectance itself is significantly weaker and spectral features due to absorbing aerosols or fine urban modes are particularly difficult to resolve. Consequently, retrieval errors for water leaving radiances in the VIS channels using the SWIR bands are larger than those obtained using the NIR bands. We have therefore adopted an approach where an additional constraint on aerosol path reflectance at 412nm channel is applied to the SWIR retrieval algorithm. The approach we are applying is a post-processing algorithm, following Stumph et al [5] where the 412nm channel is bio-optically estimated and other channels are corrected based on the fact that atmospheric errors scale with wavelength following a power law. To further improve the algorithm, the bio-optical estimator approach is compared against Neural Network Predictors.

WORK COMPLETED

- Two and three bands NIR algorithms for Chl retrieval were analyzed (in collaboration with A. Gitelson, Nebraska U) using synthetic, field and satellite data showing robustness of $Rrs(665)/Rrs(708)$ ratio algorithm based on MERIS bands and its efficacy for retrievals confirmed.
- New algorithms for the detection and classification of *K. Brevis* blooms were developed which utilize the difference signal at 2 red bands 667 and 678 nm on MODIS and similar bands on MERIS. It is shown that algorithm is less sensitive to the presence of CDOM and, because it uses the difference in two adjacent signals, to atmospheric corrections than algorithms based on Chl estimations from blue-green bands. This new algorithm (RBD) combined with a second normalizing algorithm, KBBI, is shown to be effective for detecting *Karenia Brevis* and distinguishing it from other algae.
- The performance of the neural network algorithm with and without the addition of UV channels for retrieving the IOP components from remote sensing reflectance was tested on synthetic and field data and showed some improvements with the inclusion of UV bands.
- A newly developed Stokes vector spectroradiometer was used to obtain accurate and reliable *in situ* hyperspectral and multi-angular measurements of polarization characteristics of the underwater and above water light fields in various water conditions. The angular and spectral dependence of the degrees of polarization (DOP) was analyzed, correlated to the water constituents and compared with radiative transfer models for the improved characterization of water parameters.
- The measured underwater polarized radiances were used to numerically reproduce the polarized images for underwater horizontal imaging system and to estimate the polarized components of the background veiling light. The blurring effects were modeled by point spread functions obtained from the measured volume scattering functions. It is shown that the underwater imaging visibility can be improved for unpolarized targets by using a polarizer oriented orthogonally to the partially polarized direction of the scattered veiling luminance.
- To optimize the 412nm estimator used to provide post-processing corrections on SWIR algorithms using Neural Networks we find the optimal channel selection is 490-510-555 and 670nm. We find that including the 443nm channel results in strong errors due to errors in operational atmospheric correction and should be left out.

- A Neural Network (NN) based approach was implemented to explore the optimal estimator performance that can be expected for 412nm estimation. In particular, mean errors < 40% are observed compared top bio-optical estimates ~ 100%.
- Direct intercomparisons were made of SeaDAS, insitu and regional algorithms which show potential for improvement.
- A suitable site for the new offshore platform was found in the Western Long Island Sound. Water characteristics near the platform were analyzed and showed small spatial variability necessary for the comparison with the satellite data. Temporal variability will allow validation for the range of parameters typical of coastal waters. SeaPRISM and HyperSAS instruments were acquired, successfully tested in the laboratory conditions and an installation designed which is now in the process of completion on the Long Island Sound platform.

RESULTS

Analysis of methodologies for the enhancement of algorithms for IOP retrieval from reflectance spectra based on additional measurements in the NIR and UV

Estimation of Chlorophyll-a in Coastal Waters using Red and Near Infrared Bands

It was found that 2-band Red-NIR algorithm $R_{rs}(708)/R_{rs}(665)$, which uses MERIS bands, provides a good estimation of chlorophyll concentration for $[Chl] > 5 \text{ mg/m}^3$ with a weak dependency on variation in CDOM concentrations. While obvious sensitivity to mineral concentration was observed it can be partially pared by the addition of $(1 + 25 \cdot R_{rs}(665))$ term to the numerator. Sensitivity to the fluorescence quantum yield in the range 0.25 – 1% is noticeable only for $[Chl] > 60 \text{ mg/m}^3$. 2-band algorithms, which use in numerator MODIS and MERIS bands around 750 nm, showed worse performance. Errors can be even higher on the proximal sensing and satellite data because of the low $R_{rs}(753)$ values. According to the tests on synthetic datasets, 3-band algorithm $[R_{rs}^{-1}(665) - R_{rs}^{-1}(708)] \times R_{rs}(753)$ had similar dependency on CDOM and mineral concentration and fluorescence quantum yield as the 2-band $R_{rs}(708)/R_{rs}(665)$ algorithm. Inclusion of $R_{rs}(753)$ also has a potential of error increase due to the low reflectances at this band. Advantages of 3-band algorithms need to be further studied on synthetic data with higher $[Chl]$ concentrations as well as on datasets which trace more accurately the change of specific chlorophyll absorption with $[Chl]$ due to the packaging effect.

Relationships of $[Chl]$ vs $R_{rs}(708)/R_{rs}(665)$ and $[Chl]$ vs $[R_{rs}^{-1}(665) - R_{rs}^{-1}(708)] \times R_{rs}(753)$ established recently from MERIS spectra and field data match very well synthetic data which confirms accuracy of the field and synthetic data as well as stability of these relationships. Comparison of $[Chl]$ values from Hydrolight generated datasets [6] and algorithms established from MERIS reflectances and field $[Chl]$ data [7] for 2 and 3- bands algorithms is shown in Fig. 1 and are seen to show excellent correlations. It is planned to exploit these important results in future work.

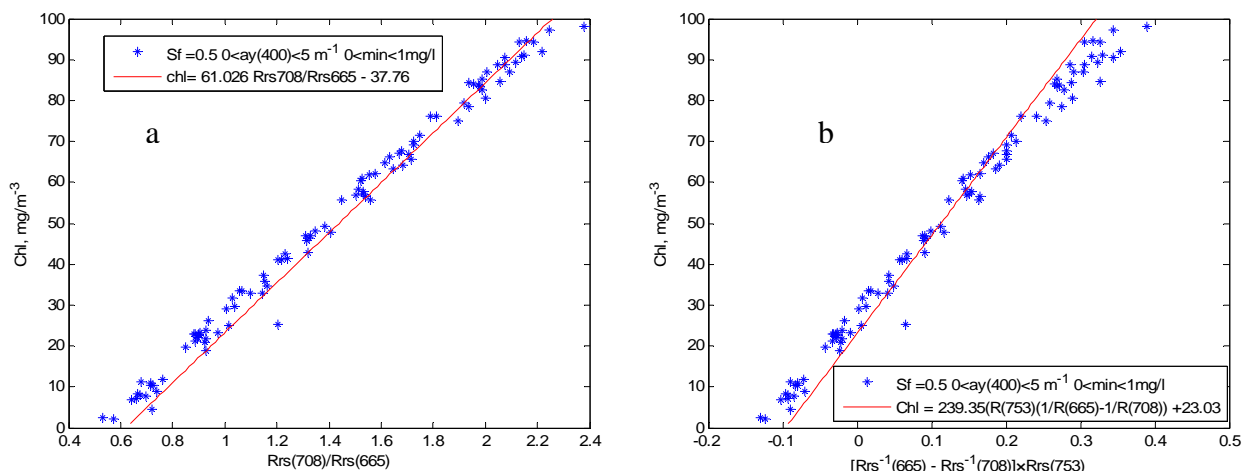


Fig. 1. Estimates of chlorophyll-a concentrations from generated reflectance spectra using calibrated Red-NIR MERIS algorithms: a) 2 band algorithm, b) 3 band algorithm.

Novel Optical Techniques for Detecting and Classifying Toxic Dinoflagellate Karenia brevis Blooms Using Satellite Imagery

Karenia brevis (K. brevis) blooms are of great interest and have been commonly reported throughout the Gulf of Mexico. We proposed a detection technique for blooms with low backscatter characteristics, which we name the Red Band Difference (RBD) technique, coupled with a selective K. brevis bloom classification technique, which we name the K. brevis Bloom Index (KBBI). The proposed techniques take advantage of the fact that because of lower backscatter characteristics in K. brevis blooms, the red peak in the reflectance signal is dominated chlorophyll fluorescence rather elastic scattering. The proposed techniques are applied to the detection and classification of K. brevis blooms from Moderate Resolution Imaging Spectroradiometer (MODIS) ocean color measurements off the Gulf of Mexico. To assess the efficacy of the techniques for detection and classification, simulations, including chlorophyll fluorescence (assuming 0.75% quantum yield) based on K. brevis blooms and non-K. brevis blooms conditions were performed. These show that effective bloom detection from satellite measurements requires a threshold of $RBD > 0.15 W/m^2/\mu m/sr$, corresponding to about of chlorophyll. While blooms are still detected at lower concentration for lower RBD thresholds, false alarms also increase. The KBBI classification technique is found most effective for thresholds of $RBD > 0.15 W/m^2/\mu m/sr$ and $KBBI > 0.3 * RBD$. The techniques were applied and shown to be effective for well documented blooms of K. brevis in the Gulf of Mexico and compared to other detection techniques, including FLH approaches, and impacts of different atmospheric corrections examined.

Reflectance spectra typical for *Karenia Brevis* bloom conditions were simulated and compared with similar conditions in Case 1 (open ocean), Case 2 (coastal) waters and non – *Karenia Brevis* conditions. Results of this modeling are shown in Fig. 2 which was also used to determine the boundaries of applicability for proposed algorithms.

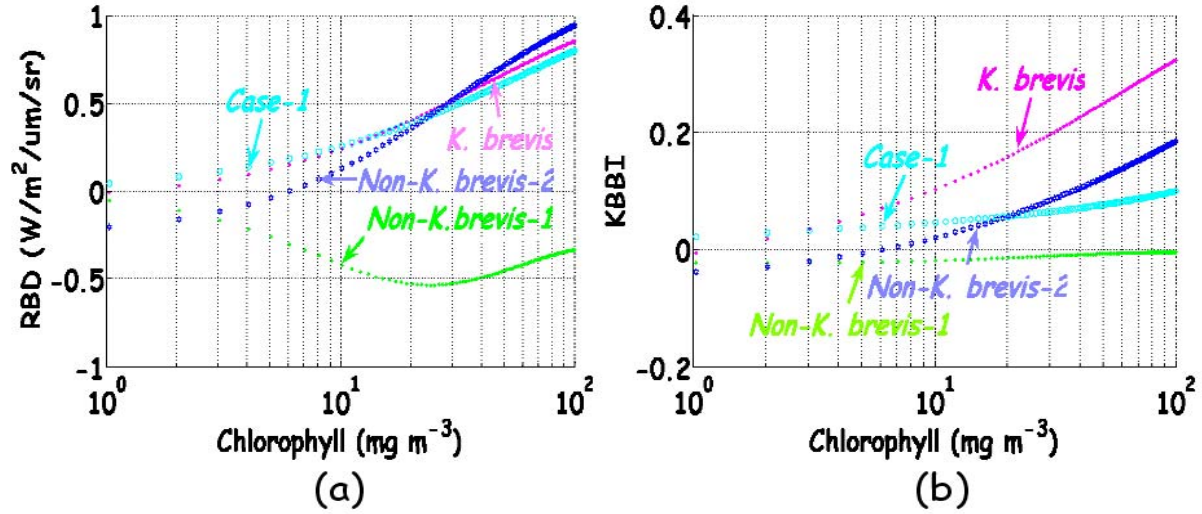


Fig. 2. Modeled (a) RBD ($\text{W/m}^2/\mu\text{m/sr}$) and (b) KBBI values as a function of chlorophyll concentrations generated for *K. brevis* blooms (magenta), non-*K. brevis*-1 (green), non-*K. brevis*-2 (purple), and Case-1 (cyan) waters. $a_{dg}(440) = 0.25\text{m}^{-1}$

Examples of tracing *Karenia Brevis* blooms on the Florida West Coast are shown in Fig. 3.

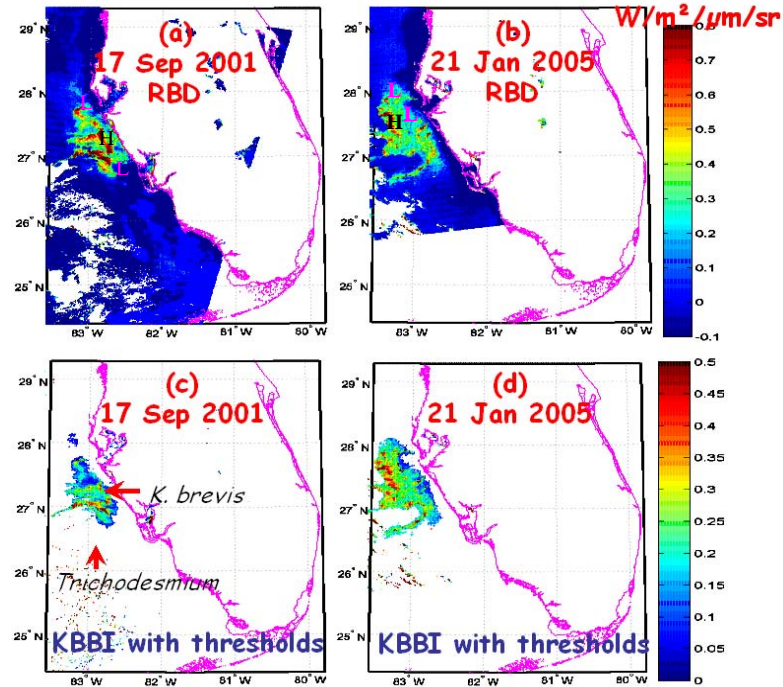


Fig. 3. *K. brevis* blooms detected using the RBD technique on the WFS on (a) 17 Sep 2001, and (b) 21 Jan 2005. These blooms are classified as *K. brevis* blooms using the KBBI classification technique with appropriate thresholds applied on (c) 17 Sep 2001 and (d) 21 Jan 2005. The 17 Sep 2001 image is an example when *K. brevis* and *Trichodesmium* blooms were co-occurring spatially but only *K. brevis* bloom is detected.

Utilization of underwater and above water polarization components of reflectance spectra for the improvement of particle type discrimination and algorithm development

Several measurement campaigns in a variety of coastal waters were carried out to test the new Stokes vector spectroradiometer developed by the CCNY Optical Remote Sensing Laboratory for above and below water measurements of polarization characteristics under sunlight illumination. These tests were in conjunction with additional standard instrumentation needed for comprehensive water characterization. Campaigns included: i) Hudson River (NY) waters, which are typically low on Chl concentration and have various concentrations of minerals, depending on tide conditions and the distance from NY Harbor. (June – July 2009), ii) Above water polarization measurements (using R/V Paumanok, Stony Brook University) in the NY-NJ area in conjunction with continuous in water measurements of optical properties using a towed (WET Labs) package, and including participation of (M. Twardowski group, (July 2009), iii) Above and below water measurements at multiple stations ranging from clear offshore waters (30 miles out) to the turbid waters of Chesapeake Bay, (using the R/V Fay Slover, stationed at the NOAA facility, Norfolk, VA together with Old Dominion University for the validation of CALIPSO satellite mission and future missions with the polarimeters on board (August 2009).

Polarization measurements were complemented by measurements of water optical properties (absorption, attenuation, backscattering, fluorescence, particle size distribution) and reflectances as well as water sampling by CCNY or partner instruments. All acquired data are being processed. First results are shown below in Fig. 4.

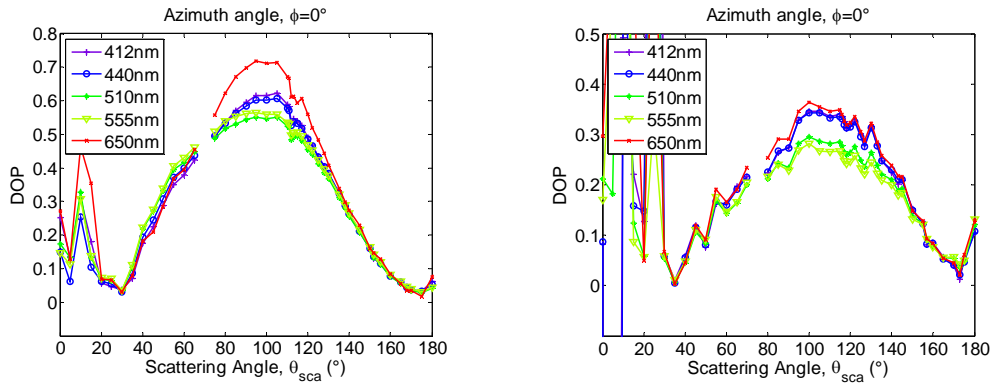


Fig. 4 Degree of polarization (DOP) as a function of scattering angle for 5 wavelengths and 2 types of waters: clear water (left), turbid water (right) VA waters 2009.

Maximum degree of polarization (DOP) measured was approx. 70% in clear waters, and less than 40% in turbid waters. The maximum is higher in the red for clear waters and in the blue and red part of the spectra for turbid waters (where absorption is higher). In both cases DOP maximum is near 100° . For scattering angles less than 30° peaks are found in both cases which are most likely due to light propagation through the air-water interface.

In Fig. 5 the match is shown between the DOP measured in below water measurements to measurements above the surface, as well as comparisons to above water DOP simulations using a NASA GISS program [8] based on measured water optical properties. The best match was achieved for

the particle index of refraction $n = 1.16$. This indicates the potential for the retrieval of additional water parameters from polarization measurements.

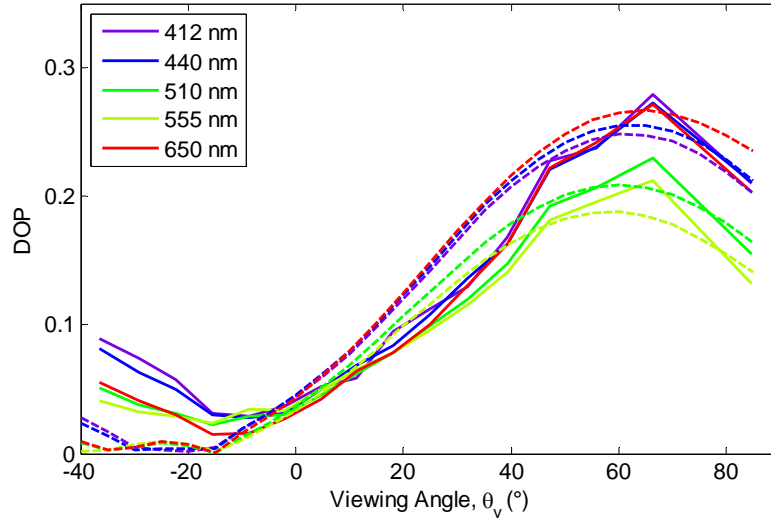


Fig. 5. Plots of DOP_t vs. viewing angle, where 0° corresponds to the observer looking down. The solid lines represent the values of DOP_t calculated from in situ underwater measurements. The dashed lines are the results of the vector radiative transfer program with $n_{nap} = 1.16$.

Improvement in retrievals of water leaving radiances for productive coastal waters obtained by adding the 412nm channel to the SWIR coastal algorithm

We explored on real data sets that we obtained from the Chesapeake Bay and assessed the performance of an a posteriori processing approach which corrects for errors due to operational atmospheric processing based on an estimate of the 412 water leaving reflectance, in turn based on other spectral channels in the VIS and NIR and assuming the errors propagate as a power law spectrally (i.e. based on Stumpf's absorbing aerosol approach) but optimized to non-aerosol layers. Comparisons were made using SWIR retrievals from the SeaDAS operational algorithm for the Chesapeake Bay area (as seen in Fig. 6). The results of the intercomparisons are shown in Fig. 7 for both the standard SWIR and the post processed retrievals. Without post-processing, we note several cases where the 443 reflectance is negative and can be traced to the presence of moderately absorbing aerosols. However, it is clear that the post processing eliminates negative retrievals. We also see significant improvement when post processing is done on sites 11-14 in comparison to the SWIR algorithm. Unlike the previous case, these matchups occur in the coastal ocean outside at the mouth of the Chesapeake Bay area (see Fig. 6) where the SWIR processing is not expected to be optimum. However, even in these cases, a significant improvement is observed in the magnitude of the retrieval. We note that the optimal choice of spectral exponent that we had originally found ($n \sim 3$) as opposed to the exponent $n=6$ used by Stumpf provide a small improvement.

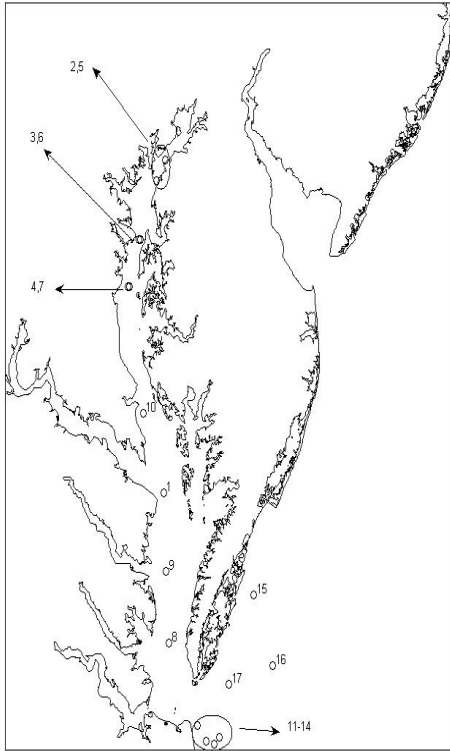


Fig. 6. Mapping of insitu matchups : non absorbing cases in Bay (1-4), absorbing cases in Bay (5-10) , non-absorbing cases outside Bay (11-17).

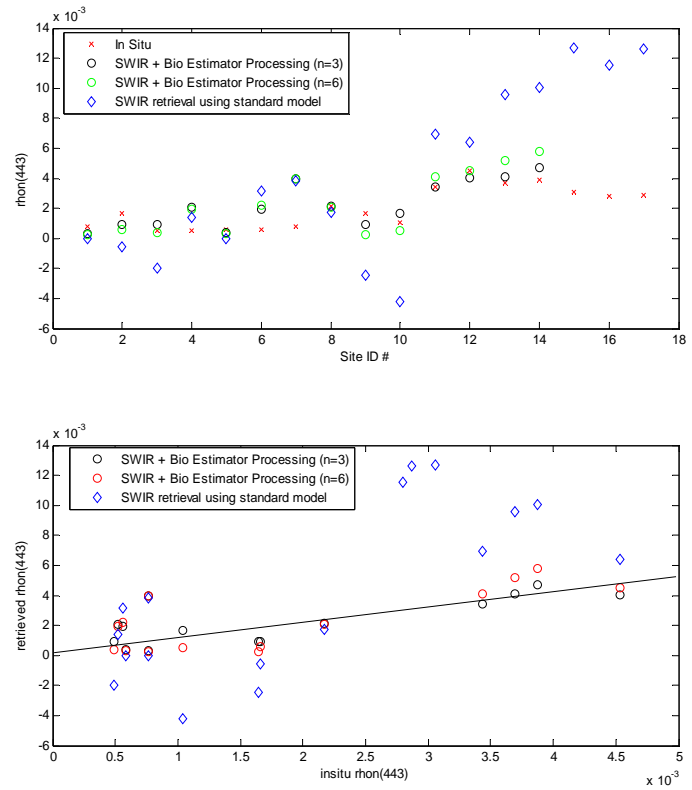


Fig. 7 a) Matchup of retrieved water leaving reflectances at 443 nm vs insitu measurements for all suitable sites b) correlations between retrievals and insitu reflectances.

Finally, we have also explored the possibility of using Neural Network (NN) techniques to improve the performance of the 412nm estimator. As we reported earlier, the Stumph bio-estimator performance as seen in Fig 8 is highly correlated although there is a significant over bias. In particular, we note that errors on the order of 100% can be seen in the estimator. However, when we apply the NN estimator to the bands at 490nm, 510nm, 555nm and 670nm, a significant improvement in the estimator is observed as seen in Fig. 9. In particular, the bias is obviously removed and the mean error is reduced to 30% with R^2 values approaching .9. It should be pointed out that the estimator can also include the 443 nm band but this band is clearly affected by atmospheric contamination. Note that in particular, fractional errors based on the NN approach are unbiased and less than 40%. Application of this to reprocess data is underway.

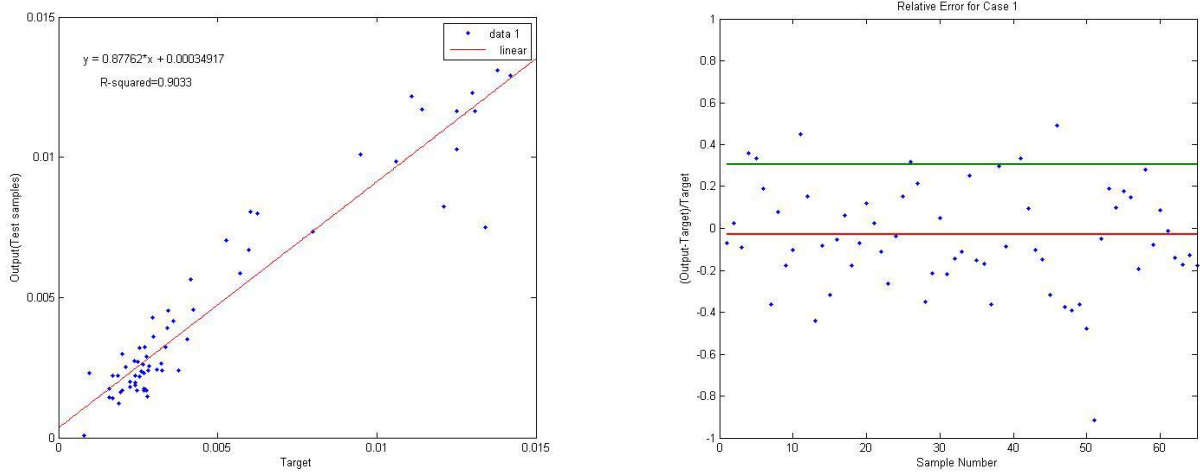


Fig. 8 Assessment of bio-optical estimator from insitu data (NOMAD Database)

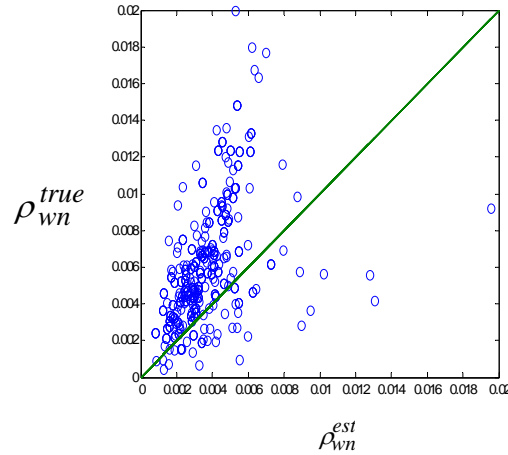


Fig. 9 NN estimator performance. a) Regression plot of estimator against insitu data, b) mean error

IMPACT/APPLICATIONS

Current algorithms for the retrieval of water optical properties based primarily on the spectral features in the blue-green region produce significant errors in coastal waters. Work by us, which includes the use of red and NIR spectral bands is shown to result in improved [Chl] retrievals in complex coastal waters. These coupled with adjacent red band difference techniques, result in retrievals that are less vulnerable to atmospheric corrections, and which, with the addition of normalizing indices, appear promising for toxic algal bloom detection and distinction.

The successful development of new techniques for the measurement of hyperspectral water polarization characteristics, has led to important understandings of the nature and parameters of underwater polarization fields, with wide-ranging of applications. Accurate measurements of water polarization properties on angular and spectral scales, made possible by our new instrumentation,

coupled with the radiative transfer simulations, is also now proving helpful in work on the improvement of in-water visibility and detection of naval targets, as well as in the retrieval of bio-optical properties.

Atmospheric correction plays a crucial role in all coastal ocean algorithms, and the work reported is advancing the development of an operational module which can be used in certain domains where the 412 reflectance is expected to be sufficiently small as well as in regionally trained areas where NN approaches or bio-optical estimators can be used.

RELATED PROJECTS

This ONR project, on improvement of retrieval of bio-optical properties, benefits from the leveraging of funding by NOAA CREST in which remote sensing of coastal waters is an important component. Starting 2009 the CCNY group also studies polarization characteristics of light in water through another award from ONR N000140911054 for years 2009-2012 with the emphasis on the underwater animals vision and camouflage applications.

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